OPERATIVE TEMPERATURE SIMULATION OF ENCLOSED SPACE WITH INFRARED RADIATION SOURCE AS A SECONDARY HEATER

L. Hach [1], *† K. Hemzal* [2], *Y. Katoh* [3]

1 Institute of Applied Physics and Mathematics, Faculty of Chemical Engineering, University of Pardubice, 532 10 Pardubice, Czech Rep.
2 Faculty of Mechanical Engineering CTU Prague, Technicka 4, 166 07 Prague, Czech Rep.
3 Department of Mechanical Engineering, Faculty of Engineering, Yamaguchi University, 755 8611 Ube, Japan

Abstract

State of indoor thermal environment became a subject of interest of several fields: energy savings, medical, comfort etc. in occupied spaces: apartments, administrative buildings, hospitals, etc. Each of them has its own specific features including requirements for accuracy of maintained feature. In this work is described the way of assessment of thermal discomfort feeling stemming from a source of heating which is often used in some rooms, a radiative heater. This effective heat source, however, has known some not quite favorable feature with respect to non-uniformity of thermal effect on surroundings. Further is discussed a way to minimize it on human thermal sensitivity.

1 Introduction

Aspirations of comfortable indoor environment in occupied space include one or more thermal parameters which would be able to characterize the way of the heat which is being transferred to the occupant. In the occupied spaces are mainly used local heat sources or integrated one into the whole system in building – central heating system. Both system have some advantages and disadvantages, however, in this work is proposed a way to compensate the non-comfortable effect of radiant heater – its inability to warm the heated space more uniformly.

2 Thermal Comfort Parameters

2.1. Operative and Globe Temperatures

As current building codes strive to specify criteria for IAQ, some of them may use empiric or semi-empiric approach. In addition, for human thermal sensibility has been found a statistical range among thermal or other sensual feelings, therefore the statistical character of relevant criteria will be accounted for. Those parameters include various indices [5], [6]: PPS, PMV, PPD, etc., which are often used nowadays. While the thermal comfort is described as a person's psychological state of mind [7] and therefore is usually referred to in terms of whether someone is feeling too hot or too cold, the above mentioned criteria are composed of several 'subsidies', i.e. physical quantities, which could be measured directly: air temperature, radiant temperature, humidity and air velocity. The four basic environmental variables define the thermal state of indoor environment and measurement devices and instruments may determine it with satisfied accuracy. The exemption represents the radiant temperature reflecting actual thermal effect from heating source on surroundings. The surface characteristics of surroundings (color, surface roughness) affect the ability to accumulate or reflex the infrared electromagnetic wave. For the outcome is well defined the mean radiant temperature t_{mr}:

$$t_{mr} = \sqrt[4]{\sum_i F_{p-i}\left(t_i + 273\right)^4} - 273 \qquad (1)$$

In Eq. (1) symbols denote: t_i – surface temperature of i-surface part (component) [^{o}C],
F_{p-i} – angle factor between the person and surface i [-].

The mean radiant temperature t_{mr} is a part of the operative temperature, the one what humans experience thermally in a space. The operative temperature is numerically the average of the (indoor) air temperature t_a and the mean radiant temperature t_{mr}, weighted by their respective heat transfer coefficients of convection (h_{cv}) and radiation (h_r):

$$t_0(\tau) = \frac{h_{cv}(\tau)t_a(\tau) + h_r(\tau)t_{mrt}(\tau)}{h_{cv}(\tau) + h_r(\tau)} \quad (^{\circ}\mathrm{C}), \tag{2}$$

which typically equates to the arithmetic average of the indoor air and mean radiant temperature in the enclosure. Together with indoor air temperature t_a is calculated operative temperature (EN ISO 7730):

$$t_o = A \cdot t_a + (1 - A) \cdot t_{mr}, \tag{3}$$

where t_o is the operative temperature [^{o}C], t_a is the air temperature [^{o}C], t_{mr} is the mean radiant temperature [^{o}C], A is a factor accordance to the relative air velocity (A = 0.5 for var = 0.2 m/s, A = 0.6 for var = 0.2-0.6 m/s, A = 0.7 for var = 0.6-1.0 m/s).

With assumption of low velocities of the indoor air within the occupied zone (< 0.2 m.s^{-1}), the simplified design of the operative temperature formula t_o:

$$t_O = \frac{1}{2}(t_i + t_{mrt}) \tag{4}$$

was used instead Eq. (3).

2.2. Globe (Indoor) Temperature versus Operative Temperature [5] (Operative Temperature Range [4])

With standards terms introduced above the term 'operative temperature' is used as the temperature referring to the uniform temperature of an imaginary black enclosure, in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment. Standard ASHRAE 55-1992 approaches *effective temperature* (t_{ef}) and *operative temperature* (t_o) as arbitrary indices that combine into a single number the effects of the dry-bulb temperature, humidity and air motion on the sensation of warmth or cold felt by the human body. Since under the presumption of a fixed moisture value the effective temperature almost equals the operative temperature defined by Eq. (2), here after it would not be used as redundant term. The globe temperature t_g is directly measured by a globe thermometer (Vernon, 1930) on which surface would be reached the thermal equilibrium when the heat gain by radiation equals the heat loss by convection, i.e.

$$q_c = q_r. \tag{5}$$

Furthermore, For low air velocity w < 0.2 m.s^{-1} it is possible to replace operative temperature with the globe temperature $t_g = t_o$. The operative temperature spans between values which, theoretically, no more than 20 % of the occupants during daylight, assuming they wear the same level of clothing insulation and with primarily sedentary activity, will find the environment thermally unacceptable. This yields states as quoted in Table 1:

Table 1: *Required thermal states in winter period for interiors with acceptable range of 80% (90%)* [4], [5].

Relative Humidity Range	Operative Temperature
50 % *RH* for 80 %*	20,5 … 24,5 ºC
50 % *RH* for 90 %*	21,3 … 23,7 ºC

* percentage level of acceptability

In Table 1 are extracted values required to be anywhere within the defined occupied zone *OZ* in the winter period if 80 %, resp. 90 % of the acceptability level will be reached, otherwise thermal comfort criteria within the occupied zone would not be met.

The acceptable range of operative temperatures and humidity for the heating season is often drawn on a psychrometric chart, in Fig. 1 the shadow areas, and is mentioned in international/state standards:

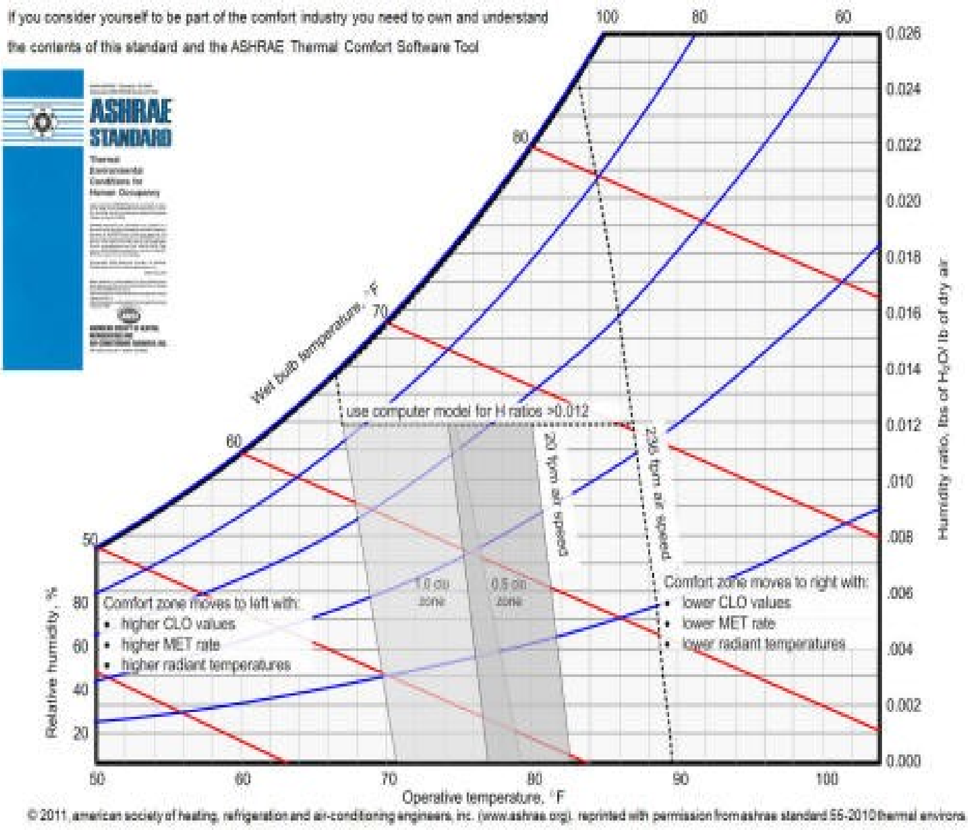


Figure 1: Thermal indoor conditions (shadow areas) for human occupancy in modified psychrometric chart (ANSI/ASHRAE Standard 55): operative temperature (x-axis), humidity (y-axis), metabolic rate, clothing and air velocity.

3 Local Thermal Discomfort with Radiant Heating System

3.1 Criteria of Local Thermal Discomfort

Criteria for local thermal discomfort such as draught, vertical air temperature differences, indices for CO_2-concentration, local mean age of air (LMA) and floor surface temperatures may assess the magnitude of discomfort via the determined appropriate statistical quantity. In the same way it is possible to handle the radiant temperature asymmetry. It is caused by cold surrounding walls (uninsulated parts, windows, cold or heated equipment) which unilaterally generates vertical or horizontal temperature gradients in occupant's immediate vicinity (occupied zone).

The installed (infrared) radiant heater acts as an amplifier of the above mentioned temperature gradients and it was investigated experimentally and through the mathematical model. The model would reflect the basic design of the space in order to fit adequately the local radiant temperature asymmetry. The basic criteria can be found in ISO EN 7730 [7] or national codes. The main parameter characterizing the unilateral thermal sensibility - Radiant temperature asymmetry – is defined as the difference between the plane radiant temperatures of the two opposite sides of a small plane element. To evaluate it, the averages temperatures of the surrounding surfaces - adequate parts of floor, walls and ceiling – were measured and then the parameter calculated.

3.2 The Procedure of Acquiring the Plane Radiant Temperatures

The temperatures including the globe temperature and indoor air temperature were evaluated in a screening period (sample time 5 min) and the programmed value set time intervals separately from the daytime and records data into a temperature matrix **TM**, Fig. 2:

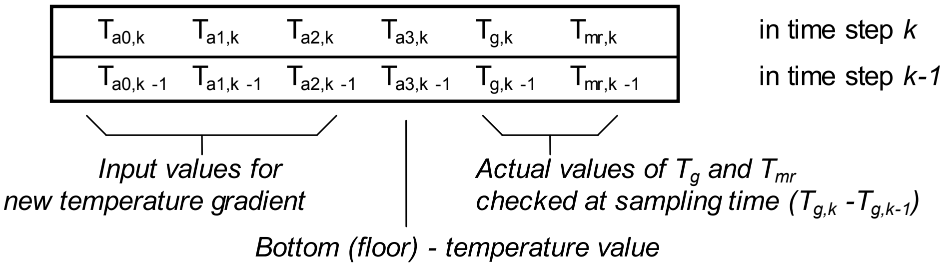
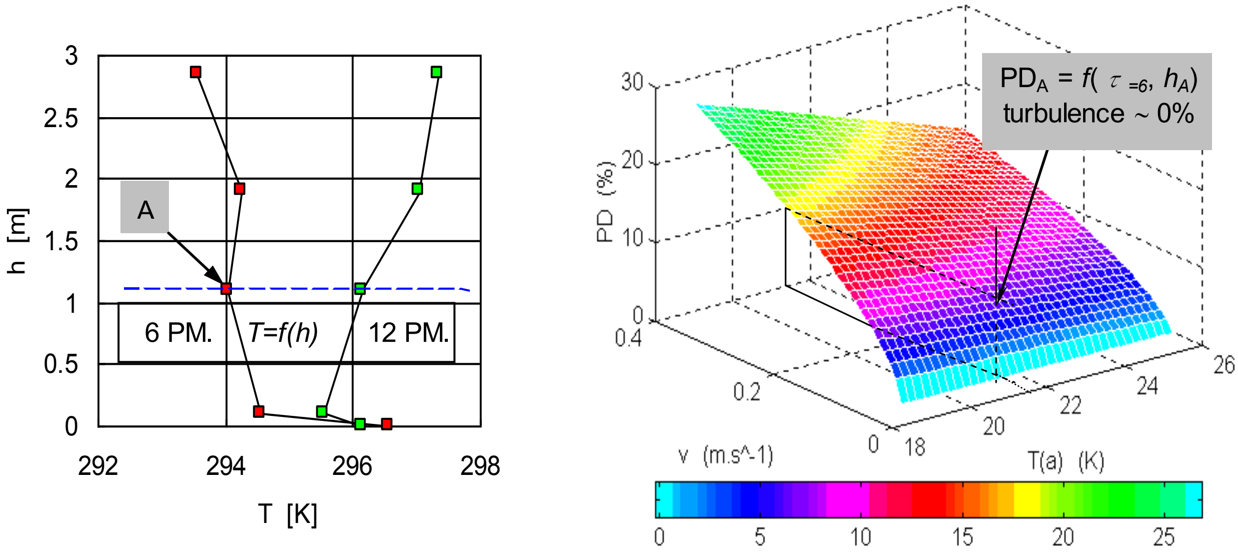


Fig.2: **TM**-*matrix structure with records of vertical profiles in two immediate screening intervals* $T_{a,k-1}$ and $T_{a,k}$.

The demanded operative temperature (programmed value of $t_{o,pr}$ = 21 °C) was assigned for work hours – the time of occupant(s) presence at the height of 1.1 m above the floor for the sedentary activity of the occupant (office work), [6]. The heater's power change then affected the radiant temperature asymmetry, as it is shown in the Fig. 3a:



a) *b)*

Fig.3: a) Vertical temperature profiles in center of the enclosed space. Recorded at 6 P.M. (red-dots profile) and at 12 P.M. (green-dots-profile), ACH ≈ 1,0.
b) Adequate covering of entire comfort zone with calculated PD-index for 0 % of air turbulence intensity; v – ambient air velocity, T(a) - ambient air temperature.

The advantage of using the Simulink/Matlab environment for the procedure includes monitoring the measured surface temperatures and calculating the operative one according the above Eq. (3) or (4) and filling the **TM**-matrix at the sampling time scheme, Fig. 2. Matrix **TM** is initially filled with temperatures collected across a vertical temperature profile in the center of the space, however, it also keeps the values collected in the immediately previous time step synchronized with the sampling time period $\Delta\tau$ (5 or 15 minutes). Finally, the evaluation then follows as simple comparison of the acceptable range of maximal difference (3.5 °C) between head and foots of the occupant, which is considered as the limit value for thermal discomfort [4].

3.3 The PD-Index as Complementary Parameter

PD-index as the thermal parameter proposed in the next chapter is calculated as complementary to the operative temperature t_o. It expresses thermal sensibility of the occupant due to the draft, which may occur with the local radiant temperature asymmetry. The permitted range of temperatures and air velocities shows Fig. 3b, Simulink scheme shows Fig. 4 below:

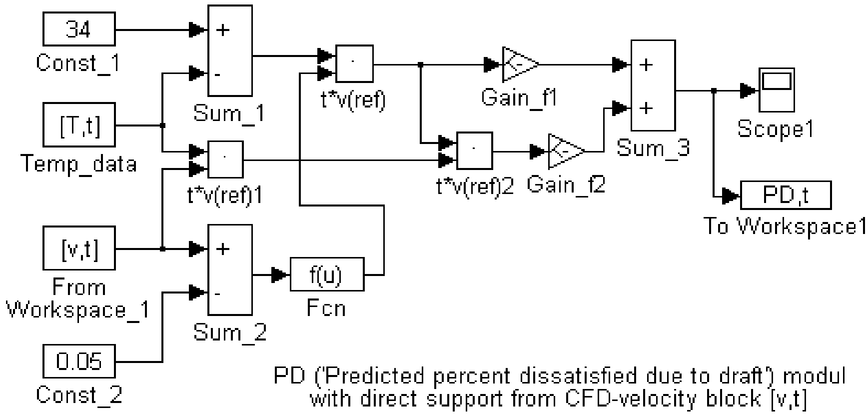


Fig. 4: *PD-index block diagram with CFD-data direct input – vector blocks [T,t] (ambient air temperature) and [v,t] (velocity field); t denotes sampling time $\Delta\tau$.*

Apart from the semi-empirical feature of the operative temperature measured as a globe temperature as described above, there are many more theoretical models, both deterministic and empirical [2], [5]. For the complex solution of heat transfer within the enclosure including the amount exchanged among the walls and affecting the thermal sensitivity with the air motion, one may expect some of these models to likely be included into the calculation. The closing paragraph presents the value of the *PD*-index solved for the whole vertical cross-cut-surface area projected on the space meridian in addition to operative temperature.

PD or '*predicted percent dissatisfied due to draft*', is a fit to data of persons expressing thermal discomfort due to draft's occurrence. The inputs to *PD*-index are air temperature t_a, air velocity v_a, and turbulence intensity *Tu*. Here a 'draft' is unwanted local cooling. *The draft risk* (or *PD* equation) is [28]:

$$PD = 3{,}413\,(34 - t_a)\,(v_a - 0{,}05)^{0{,}622} + 0{,}369\,v_a.Tu\,(34 - t_a)\,(v_a - 0{,}05)^{0{,}622} \qquad (6)$$

Tu is the turbulence intensity expressed as a percent. 0 % represents laminar flow and 100 % means that the standard deviation of the air velocity over a certain period is of the same order of magnitude as the mean air velocity. v_a is the air velocity (in meters per second) and t_a is the air temperature in Celsius degrees.

4 Conclusion

Parameter Radiant temperature asymmetry in describing the level of thermal sensibility of occupants may sufficiently characterize the part of the statistical quantity of human's thermal feeling. Because of certain effect of moving air masses in the immediate vicinity of the human skin, the additional parameter should complete the quantity. With respect to the draft, the appropriate parameter was tested the PD-index, which is possible to use also as an auxiliary signal in a controller of the heating unit.

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Contact information:

Lubos Hach
Institute of Applied Physics and Mathematics, Faculty of Chemical Engineering,
University of Pardubice, 532 10 Pardubice, Czech Rep.